

Top Quarks at Photon Colliders

Edward Boos^{a,1}

^a*Institute of Nuclear Physics, Moscow State University*

Abstract

A review of results on top quark physics expected at the Photon Linear Colliders is presented.

Key words: Top Quark, Photon Collider

1 Introduction

The top quark, with the mass slightly less than the mass of the gold nucleus, is the heaviest elementary particle found so far. The RUN1 result for the top mass measurement by the Fermilab CDF and D0 collaborations is $M_t = 174.3 \pm 3.2(stat) \pm 4.0(syst)$ (see (1)).

The top decays much faster than is typical for a formation of the strong bound states. So, the top provides, in principle, a very clean source for fundamental information. All top quark couplings to gauge bosons and other quarks are uniquely fixed in the SM by the gauge principle, the structure of generations and a requirement of the lowest dimension of the interaction Lagrangian which lead to a renormalizability and unitarity of the SM as a quantum field gauge theory.

The top is heavy and up to now point like at the same time. The top Yukawa coupling $\lambda_t = 2^{3/4} G_F^{1/2} m_t$ is numerically very close to unity, and it is not clear whether or not this takes place due to some deep physical reason. Because of unusual top properties one might expect deviations from the SM predictions to be more likely in the top sector (2). Studies of the top may shed light on the origin of the mechanism of EW symmetry breaking. Top quark physics will be a very important part of research programs for all future hadron and

¹ e-mail: boos@theory.npi.msu.su

lepton colliders. The $\gamma\gamma$ collider is of special interest because of a very clean electromagnetic production mechanism with high rate (see the review (3)).

2 Top pair production in $\gamma\gamma$ collisions

The leading order $\gamma\gamma \rightarrow t\bar{t}$ cross section is well known and has a maximum a maximum of about 420 ($++$), 450 (unpolarized) and 550 ($+-$) GeV. This cross section is larger than the corresponding e^+e^- cross section.

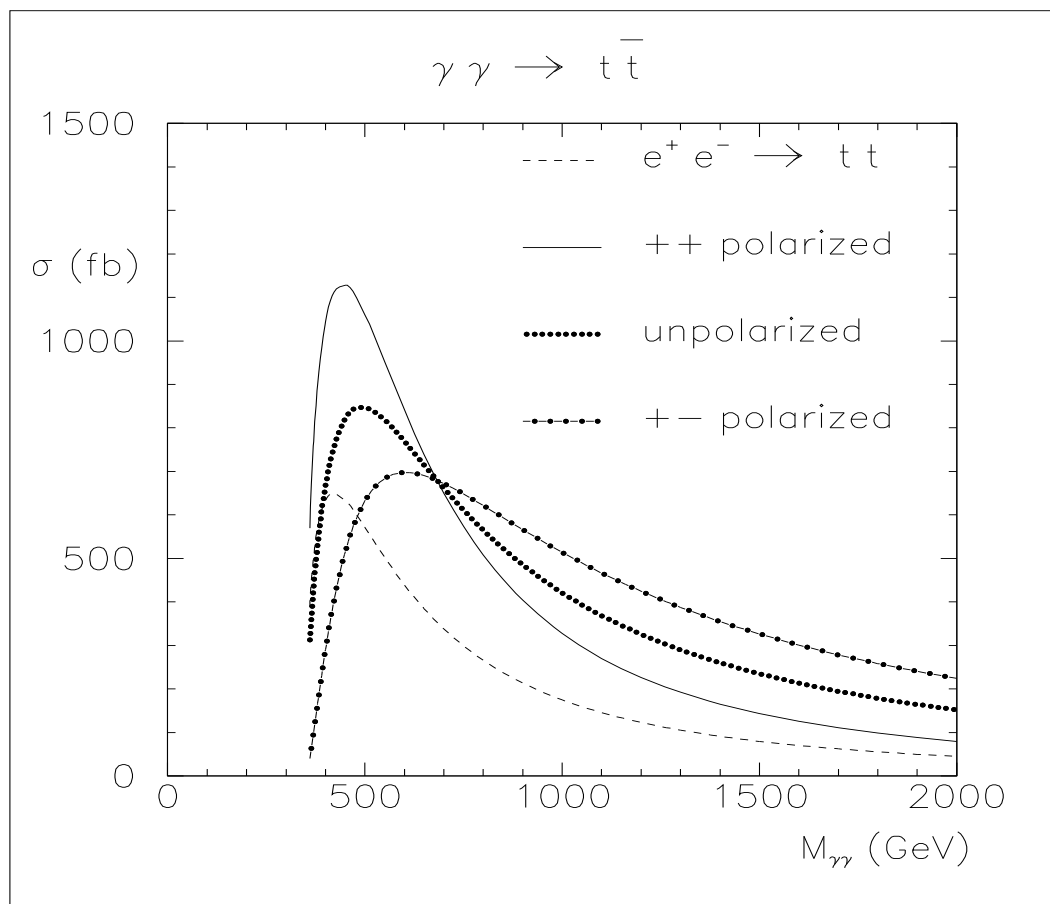


Fig. 1. Top quark pair production to LO

The $(++) = (--)$ helicity configuration ($J_z = 0$) dominates at energies less than about 680 GeV, while the $(+-) = (-+)$ or $J_z = 2$ configuration starts to dominate at higher energies.

The strong NLO corrections are large and important in the region above the threshold up to about 500 GeV. They lead to a significant increase of the rate in the $(++)$ mode. The angular cuts do not make a significant difference (4) (see Fig.2).

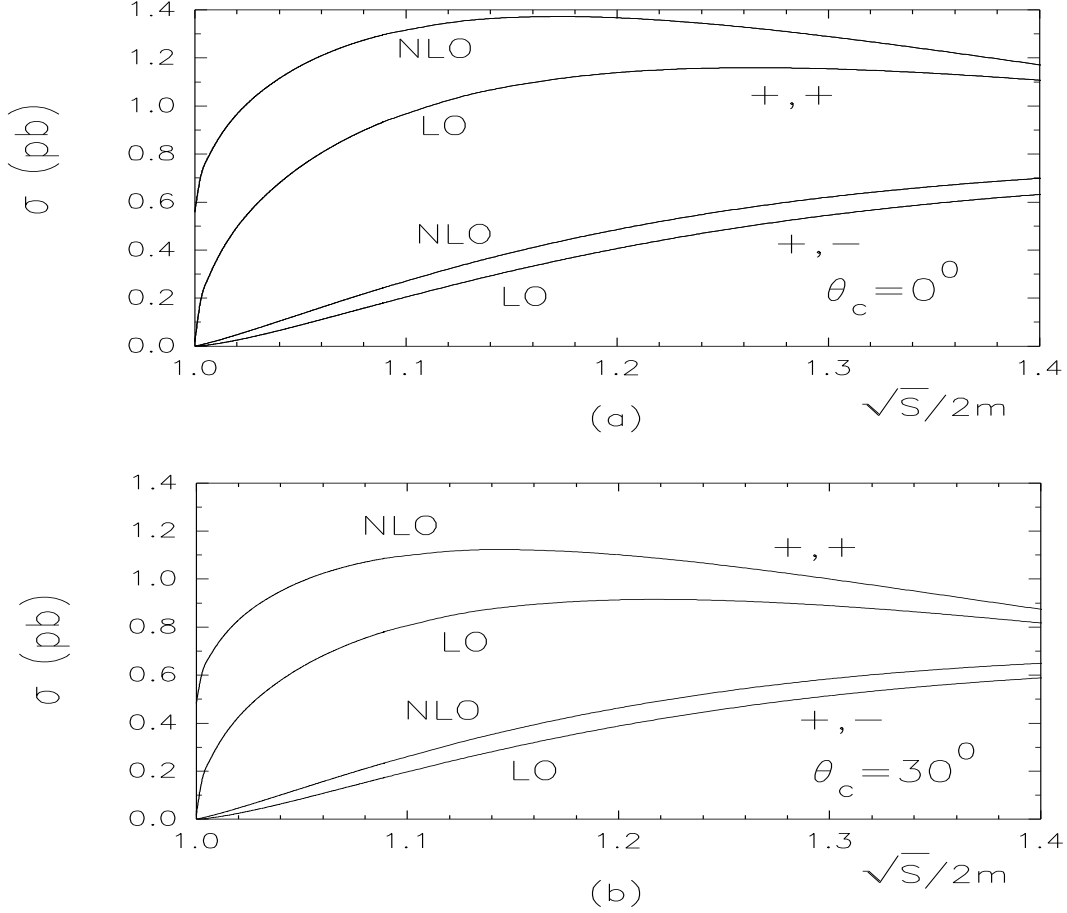


Fig. 2. NLO QCD corrected top quark pair production

The electroweak corrections are also known (5) to be on the order of 0 - (-10)% up to 1TeV energies. In the region close to the threshold they are about -10 % for the $J_z = 0$ case. The EW corrections are important for high accuracy predictions.

The corrections for the linear polarizations of initial photons have recently been computed (6). The results in Fig. 3 are given for $\Delta\gamma = 0$ and $\pi/2$ where $\Delta\gamma$ is the angle between the polarization vectors of colliding photons. The calculation could be important for a measurement of CP parity of SUSY Higgs particles H and A.

3 Top pair production in $\gamma\gamma$ close to the threshold

Due to the final state interactions, in order to get a reliable answer for the production cross section in the threshold region it is necessary to resum the Coulomb corrections. In this sense the situation is similar to the case of e^+e^- collisions (7).

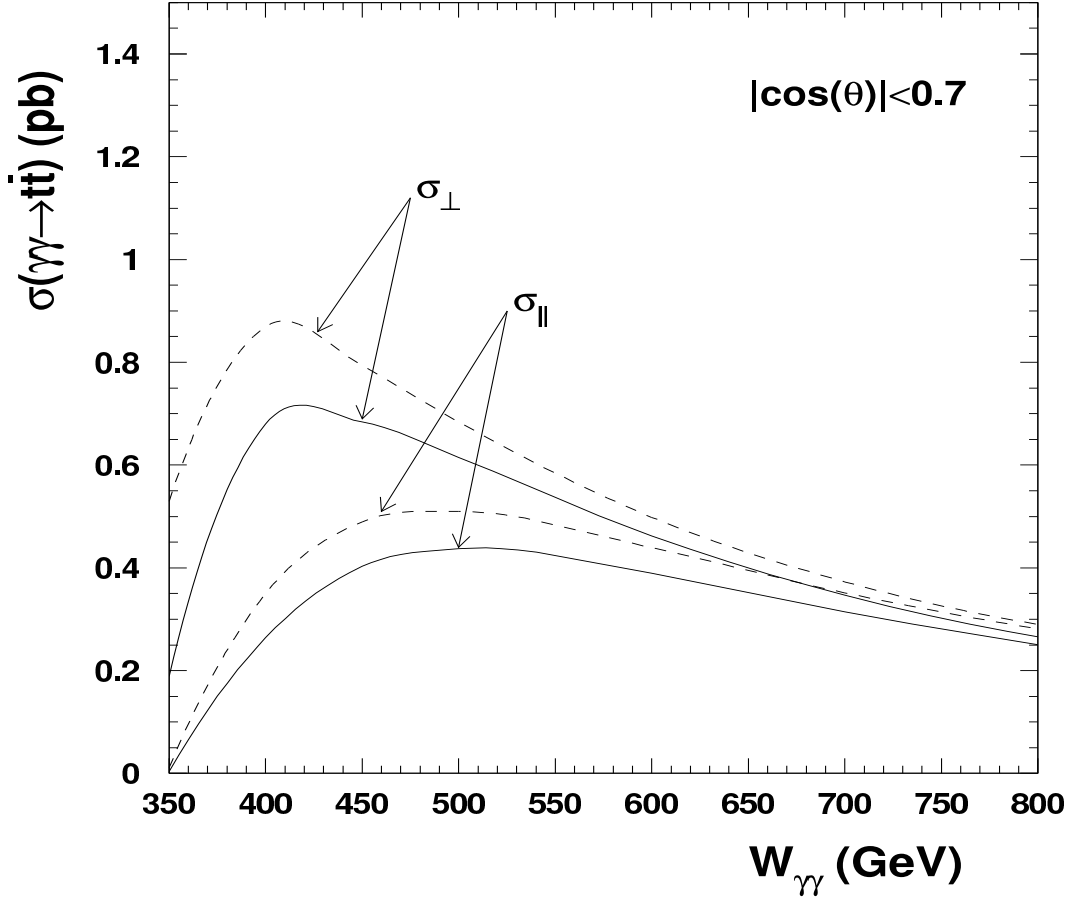


Fig. 3. Top quark pair production to NLO for the linear polarizations

After a resummation the cross section close to the threshold increases 4-5 times. The effect is specially pronounced for the $(++)$ mode of colliding photons (8).

In Fig. 4 the normalized cross section $R(\gamma\gamma \rightarrow t\bar{t}) = \frac{\sigma(\gamma\gamma \rightarrow t\bar{t})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$ is shown for unpolarized photons as a function of energy counted from threshold in the leading order (weak solid line), NLO (dotted line) and NNLO (bold solid line) for $m_t = 175$ GeV and $\alpha_s(M_Z) = 0.118$. The “soft” normalization scale for the gluons responsible for the Coulomb binding effects is $\mu_s = 50$ GeV. Only the known logarithmic part of the “hard” matching coefficient is used in the NNLO cross section.

However one should note that smearing related to the energy spectrum of colliding photons was not included in the calculations.

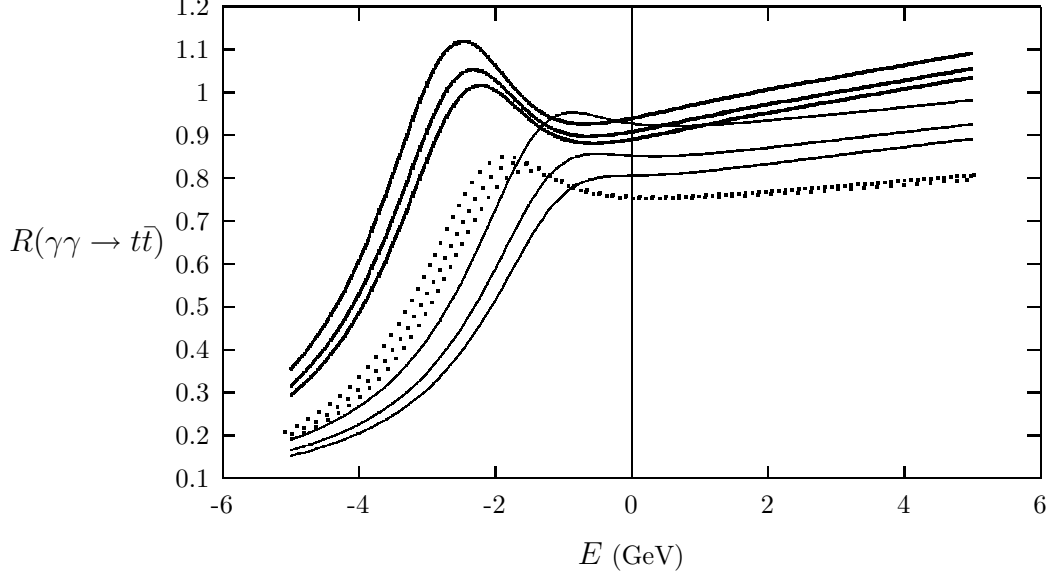


Fig. 4. The normalized cross section of top quark pair production close to the threshold

4 Probe for anomalous couplings from pair production

There are two points which are different for the case of $\gamma\gamma$ and e^+e^- collisions with respect to the couplings:

- in $\gamma\gamma$ collisions the $\gamma t\bar{t}$ coupling is involved in the 4th power
- the $\gamma t\bar{t}$ coupling is separated from $Zt\bar{t}$ coupling in $\gamma\gamma$ collisions while in e^+e^- collisions both couplings are involved.

One can use the following effective Lagrangian which includes anomalous form-factors in a general model independent way:

$$L_{eff} = ie_0(f_1^\alpha \gamma_\mu + \frac{i}{2m_t} f_2^\alpha \sigma_{\mu\nu} q^\nu + f_3^\alpha \gamma_\mu \gamma_5 + \frac{i}{2m_t} f_4^\alpha \sigma_{\mu\nu} \gamma_5 q^\nu),$$

where $\alpha = \gamma, Z$, and, of course, only couplings with $\alpha = \gamma$ occur in $\gamma\gamma$ collisions.

It was demonstrated (9) that if one can measure the cross section with 2% accuracy one will be able to probe Λ upto 10 TeV where the formfactors reexpressed through Λ as $f_i^\alpha \rightarrow (f_i^\alpha)^{SM}(1 + s/\Lambda^2)$ Results are shown in Fig.5.

Sensitivity to the anomalous magnetic moment f_2^γ is slightly better in $\gamma\gamma$ than in e^+e^- collisions.

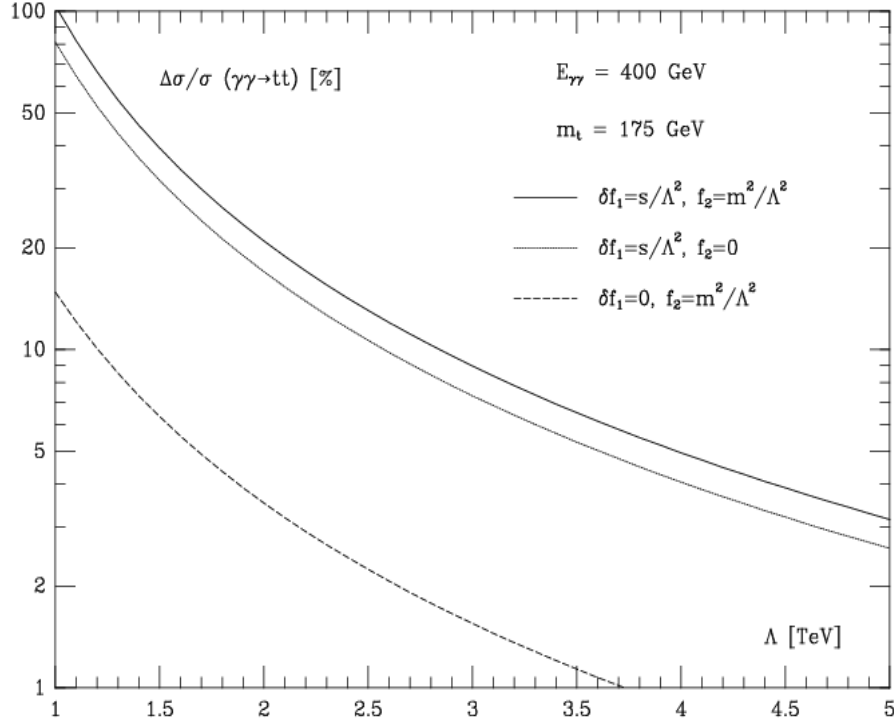


Fig. 5. Deviations from the SM cross section in %

The f_4^α term is the CP violating term. The best limit on the imaginary part of the electric dipole moment $Im(f_4^\gamma)$ is about $2.3 \cdot 10^{-17}$ (10). It comes from the forward-backward asymmetry A_{fb} with initial-beam helicities of electron and laser beams $\lambda_e^1 = \lambda_e^2$ and $\lambda_l^1 = -\lambda_l^2$. The limit for the real part of the dipole moment is also on the order of 10^{-17} obtained from the linear polarization asymmetries (11). One should stress the limit is an order of magnitude better than that obtained from 500 GeV e^+e^- collisions.

The top quark pair production in $\gamma\gamma$ collisions provides a very interesting option to study parity properties of the Higgs boson and CP violating effects (12). It was shown for the two-Higgs doublet model that there are several asymmetries which are useful for probing CP violation in the Higgs sector (13).

The problem here is that there is an interference between the H and the A with a small mass gap. A model-independent study of the effects of a neutral Higgs bosons without definite CP-parity has been done (14) where complete set of asymmetries was proposed in order to determine all the CP couplings. However, the effect is less pronounced with increasing $\tan\beta$. An expected mass

resolution for the top quark is about 5-10 GeV, and therefore it is problematic to separate signals for various polarization configurations from the background (15).

The $\gamma\gamma$ colliders will be comparable to the e^+e^- and e^-e^- in the search reach for large extra dimensions via top pair production (16).

5 Single top production in $\gamma\gamma$ and γe

Single top production in $\gamma\gamma$ collisions results in the same final state as the top pair production. Here the situation is similar to single top production at the the LHC in Wt mode (17). The top pair production rate must be removed from the total $\gamma\gamma \rightarrow Wtb$ rate (see the complete set of tree diagrams in Fig.6) in order to get the correct single top production rate. This should be done in a gauge invariant way. One can make the fit of the peak in the Wb invariant mass with the Breit-Wiegner formula and then remove the peak contribution, or one can apply a cut of ± 25 GeV around the peak position in the Wb invariant mass distribution. These two methods lead to very similar numerical results (19) presented in the Fig.7. ²

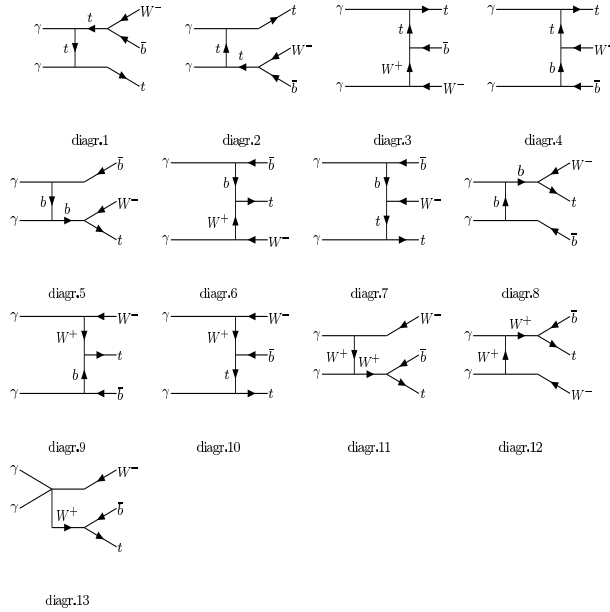


Fig. 6. Complete set of SM tree diagrams for Wtb production

Single top production in γe collisions has been discussed in several papers (20). The complete set of SM tree diagrams is shown in Fig. 8. In contrast to

² All the computations have been done by means of the program CompHEP (25)

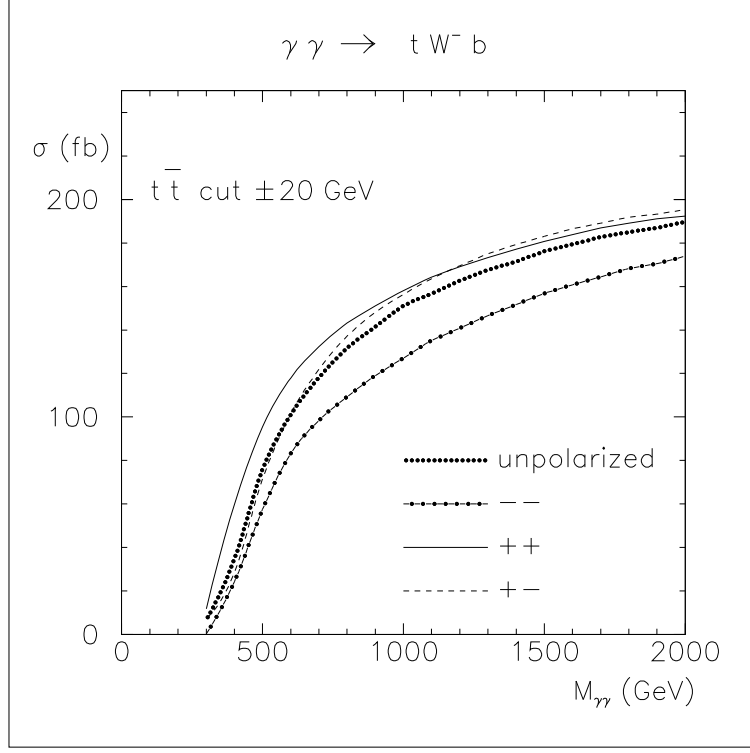


Fig. 7. Single top production rate in $\gamma\gamma$ collisions for various polarizations

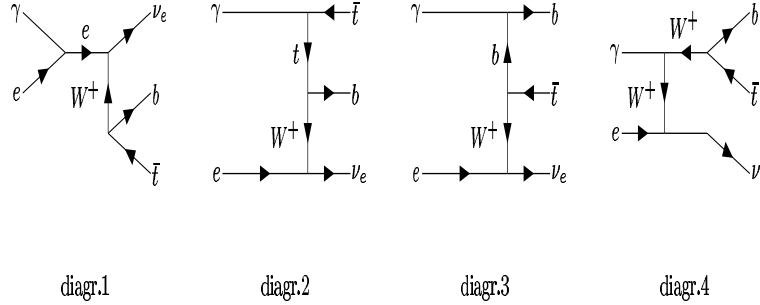


Fig. 8. SM tree diagrams for single top production in γe collisions

the top pair production rate the single top rate is directly proportional to the Wtb coupling and therefore the process is very sensitive to its structure.

In terms of the notation as from the effective Lagrangian

$$L = \frac{g}{\sqrt{2}} \left[W_\mu^- \bar{b} (\gamma_\mu f_{1L} P_- + \gamma_\mu f_{1R} P_+) t - \frac{1}{2M_W} W_{\mu\nu} \bar{b} \sigma^{\mu\nu} (f_{2R} P_- + f_{2L} P_+) t \right] + \text{h.c.}, \quad (1)$$

where $W_{\mu\nu} = D_\mu W_\nu - D_\nu W_\mu$, $D_\mu = \partial_\mu - ieA_\mu$, $P_\pm = 1/2(1 \pm \gamma_5)$ and $\sigma^{\mu\nu} = i/2(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)$ one can compare collider potentials for an expected accuracy of the anomalous

	F_2^L	F_2^R
Tevatron ($\Delta_{sys.} \approx 10\%$)	$-0.18 \div +0.55$	$-0.24 \div +0.25$
LHC ($\Delta_{sys.} \approx 5\%$)	$-0.052 \div +0.097$	$-0.12 \div +0.13$
γe ($\sqrt{s_{e^+e^-}} = 0.5$ TeV)	$-0.1 \div +0.1$	$-0.1 \div +0.1$
γe ($\sqrt{s_{e^+e^-}} = 2.0$ TeV)	$-0.008 \div +0.035$	$-0.016 \div +0.016$

Table 1

Expected sensitivity for Wtb anomalous couplings measurements

parameter measurements presented in the table 1. The notations are related to those from other studies (21) by the formula $f_{2L(R)} = \frac{C_{t(b)W\Phi}}{\Lambda^2} \frac{v\sqrt{2}m_W}{g}$, where Λ is the scale of new physics.

In the table 1 (18) uncorrelated limits on anomalous couplings from measurements at different machines are shown. One can see the best limits one can reach at very high energy γe colliders even in the case of unpolarize collisions. In the case of polarized collisions, the rate is increasing significantly as shown in Fig.9 (19) and therefore one can get better bounds. One should stress that only left handed electrons lead to a nonvanishing cross section, whereas the cross section with righ-handedt electrons is proportional to the electron mass squared and therefore nigliible.

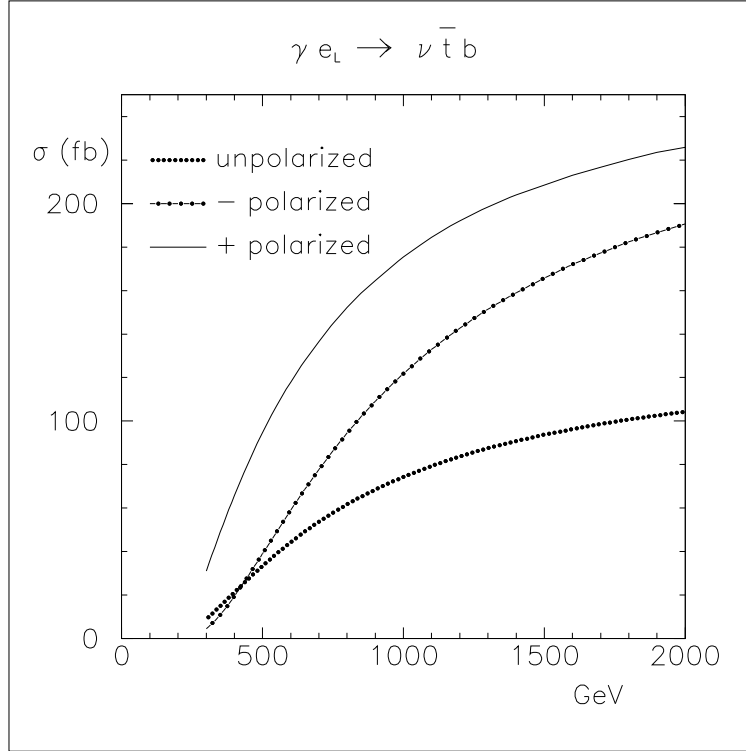


Fig. 9. Single top quark production cross section in γe collisions

Single top quark production in $\gamma\gamma$ and γe collisions provides interesting pos-

sibilities to test FCNC radiative couplings and to study various predictions of Technicolor models. The following effective Lagrangian is used to parametrize anomalous couplings:

$$L_{eff} = \frac{e}{\Lambda} (k_c \bar{t} \sigma_{\mu\nu} c) F^{\mu\nu} + h.c. .$$

k/Λ is expected to be constrained at the level of 0.12/TeV at the Tevatron with 10 fb^{-1} and 0.01/TeV at the LHC with 100 fb^{-1} integrated luminosity. At a 500 GeV $\gamma\gamma$ collider one expects a limit for k/Λ about 0.05/TeV with 10 fb^{-1} luminosity (22).

There are many variants of technicolor models. The detailed predictions are normally model dependent. However, there are predictions, like that of the existence of charged (pseudo-)scalars, which are somewhat model independent. Several studies (23; 24) of that have been done for photon colliders. If there is a large flavor mixing between the right-handed top and charm quarks it leads to a large Yukawa coupling of a charged (pseudo-)scalar with charm and bottom quarks. The dominant decay mode in Topcolor models is $\phi^+ \rightarrow t\bar{b}$. So it gives the contribution to the single top production in $\gamma\gamma$ and γe collisions (24) (see results in Fig.10).

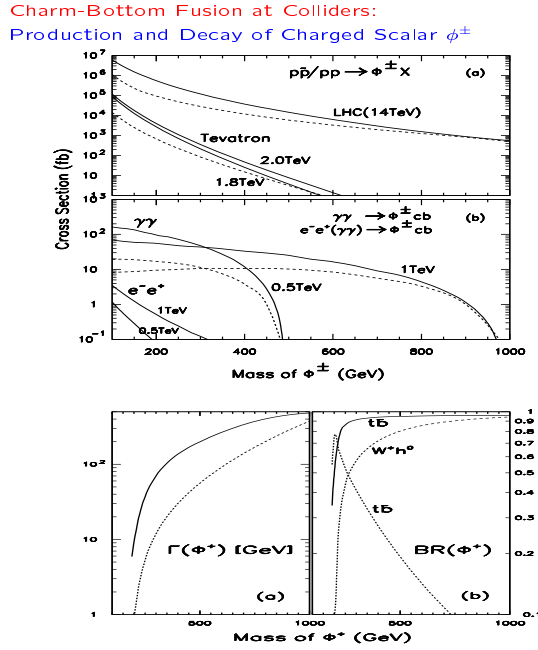


Fig. 10. Production and decay of the Technicolor charged scalar

6 Concluding Remarks and Problems

In this short review we have considered various aspects of top quark physics which can be studied at linear $\gamma\gamma$ and γe colliders.

- Top quarks could be produced at photon colliders in the top pair mode or singly. The SM production mechanisms are clean and simple. The SM cross section and distributions are known to the LO level and in several cases to the NLO level.
- Photon Linear Colliders provide a number of interesting options which are comparable and in some cases even better than those at other colliders for the study of top quark physics.
 - The top pair production rate is proportional to the coupling of a top quark with a photon in 4th power and is therefore very sensitive to its structure and possible deviations from the SM.
 - Using various asymmetries one can uniquely study CP properties of the Higgs bosons and CP violating effective operators.
 - Single top quark production at a high energy γe collider is the best collision option for the study of the structure of the Wtb coupling.
 - Single top production at photon colliders allows one to study various effects predicted by Technicolor models
- One should stress that in general, simulations of top quarks effects at photon colliders are much less developed than for e^+e^- LC and the hadron colliders Tevatron and LHC. Usually subsequent decays, jet fragmentation, a possible detector response, as well as various backgrounds have been not included in the simulations. An important problem is to simulate correctly the influence of a real photon spectrum. Much work still needs to be done.

We must apologize that not all the results obtained on the subject have been mentioned. The author thanks the Organizing Committee of the Workshop for kind hospitality and financial support. The work was partly supported by the RFBR-DFG 99-02-04011, RFBR 00-01-00704, and CERN-INTAS 99-377 grants.

References

- [1] L.Dudko, *Talk for the D0 and CDF collaborations given at 35th Rencontres de Moriond QCD, Les Arcs, France, March 2000.*
- [2] R.D. Peccei and X. Zhang, *Nucl.Phys.* **B337** (1990) 269; R.D. Peccei, S. Peris and X. Zhang, *Nucl.Phys.* **B349** (1991) 305.
- [3] J.L.Hewett, *Int.J.Mod.Phys.* **A13** (1998) 2389.
- [4] B.Kamal, Z.Merebashvili, A.P.Contogouris, *Phys. Rev.* **D51** (1995) 4808; B.Kamal, Z.Merebashvili, *Phys. Rev.* **D58** (1998) 074005.
- [5] A.Denner, S.Dittmaier, M.Strobel, *Phys. Rev.* **D53** (1996) 44.
- [6] G.Jikia, A.Tkabladze, hep-ph/0004068.

- [7] J.H.Kuehn, *Act.Phys.Pol.* **B12** (1981) 347; I.Bigi, Y.Dokshitzer, V.Khoze, J.Kuehn, P.Zerwas, *Phys. Lett.* **B181** (1986) 157; V.Fadin and V.Khoze, *JETP Lett.* **46** (1987) 525; J.Strassler and M.Peskin, *Phys. Rev.* **D34** (1991) 1500; see the last review on the subject and referces therein A.H. Hoang et al., *Eur.Phys.J.* **C3** (2000) 1.
- [8] A.A. Penin and A.A. Pivovarov, *Nucl.Phys.* **B550** (1999) 375.
- [9] A. Djouadi, J. Ng, T.G. Rizzo et al. hep-ph/9504210, Report-no: SLAC-PUB-95-6772, GPP-UdeM-TH-95-17, TRI-PP-95-05.
- [10] P. Poulose and S.D. Rindani, *Phys. Lett.* **B452** (1999) 347.
- [11] S.Y. Choi and K. Hagiwara, *Phys. Lett.* **B359** (1995) 369; M.S. Baek, S.Y. Choi, C.S. Kim, *Phys. Rev.* **D56** (1997) 6835.
- [12] M. Kraemer, J. Kuehn, M.L. Stong, P.M. Zerwas *Z. Phys.* **C64** (1994) 21.
- [13] H. Anlauf, W. Bernreuther, A. Brandenburg, *Phys. Rev.* **D52** (1995) 3803; Erratum-ibid **D53** (1996) 1725; W. Bernreuther, A. Brandenburg, P. Overmann, *Physics with e+e- Linear Colliders* (1995) 49, hep-ph/9602273.
- [14] E.Asakawa, S.Choi, K.Hagiwara, J.Lee, hep-ph/0005313, Report-no: KEK-TH-698, KIAS-P00028, OCHA-PP-160.
- [15] M.Muhlleitner, M.Spira, P.M.Zerwas, Contribution to this Proc.
- [16] T.Rizzo, *Phys. Rev.* **D59** (1999) 113004.
- [17] A.Belyaev and E.Boos, hep-ph/0003260, Report-no: CERN-TH/2000-093.
- [18] E. Boos, L.Dudko, T.Ohl, *Eur.Phys.J.* **C11** (1999) 473.
- [19] E.Boos, M.Dubinin, A.Pukhov, M.Sachwitz, H.J.Schreiber, in preparation
- [20] G.V. Jikia, *Nucl. Phys.* **B374** (1992) 83; E.Yehudai, *Talk given at 2nd International Workshop on Physics and Experiments with Linear e+ e- Colliders, Waikoloa, HI, 26-30 Apr 1993*, hep-ph/9308281; E. Boos, A. Pukhov, M.Sachwitz, H.J.Schreiber, *Talk given at Joint ECFA / DESY Study: Physics and Detectors for a Linear Collider, Hamburg, Germany, 20-22 Nov 1996*, hep-ph/9711253; E.Boos, A.Pukhov, M.Sachwitz, H.J.Schreiber, *Phys. Lett.* **B404** (1997) 119; J.-J.Cao, J.-X.Wang, J.Yang, B.L.Young, X.Zhang, *Phys. Rev.* **D58** (1998) 094004.
- [21] G.J. Gounaris, F.M. Renard, N.D. Vlachos, *Nucl. Phys.* **B459** (1996) 51.
- [22] K.J. Abraham, K. Whisnant, B.L. Young, *Phys. Lett.* **B419** (1998) 381.
- [23] Hong-Yi Zhou, et al., *Nucl. Phys. Proc. Suppl* **75B** (1999) 302; B.Wang, Y.-P. Kuang, H.-Y. Zhou, H.Wang, L.Zhang, *Phys.Rev.* **D60** (1999) 014002.
- [24] H.-J. He, C.-P. Yuan, *Phys. Rev. Lett.* **83** (1999) 28-31.
- [25] E.E. Boos et al., *INP MSU 94-36/358 and SNUTP-94-116*, hep-ph/9503280; P. Baikov et al., *Proc. of the Xth Int. Workshop on High Energy Physics and Quantum Field Theory, QFTHEP-95, ed. by B. Levtchenko and V. Savrin, Moscow, 1995* p. 101.; A.Pukhov et al., *CompHEP user's manual, v.3.3 INP MSU 98-41.542*, hep-ph/9908288.